Broad band Spectral Properties of Accreting X–ray Binary Pulsars

Mauro Orlandini

INAF/IASF Bologna, via Gobetti 101, 40129 Bologna, Italy

Abstract

Broad-band spectra of accreting X–ray binary pulsars can be fit by a phenomenological model composed by a power law with a high energy rollover above 10 keV, plus a blackbody component with a temperature of few hundred eV. While, at least qualitatively, the hard tail can be explained in terms of (inverse) Compton scattering, the origin of the soft component cannot find a unique explanation. Recently a qualitative picture able to explain the overall broad band-spectrum of luminous X–ray pulsars was carried out by taking into account the effect of bulk Comptonization in the accretion column. After a review on these recent theoretical developments, I will present a case study of how different modelization of the continuum affect broad features, in particular the cyclotron resonance features in Vela X–1.

Key words: radiation mechanism: nonthermal — accretion, accretion disks — stars: neutron — X–rays: binaries — X–rays: individual (Vela X–1, 4U 1626–67)
PACS: 95.75.Fg; 95.30.Jx; 97.80.Jp; 95.85.Nv; 97.10.Gz; 97.60.Jd; 98.70.Qy

1 Introduction

Since the observation of pulsed emission from Centaurus X–3 (Giacconi et al., 1971) and the discovery of its binary nature (Schreirer et al., 1972), more than 100 other X–ray binary pulsars (XBPs) have been observed. The qualitative physical scenario able to explain their pulsed X–ray emission was first elaborated by Shklovskii (1967) *before* their discovery: X–rays are produced in the conversion into radiation of the kinetic energy of matter coming from the stellar companion and accreting onto the neutron star (NS). Because of the interaction with the NS strong magnetic field, of the order of 10^{11}–10^{13} G, matter is driven onto the magnetic polar caps, where it is decelerated and X–rays are produced. If the magnetic field axis is not aligned with the spin axis, the NS acts as a "lighthouse", giving rise to pulsed emission when the beam crosses our line of sight. For a detailed description of the XBP spectral

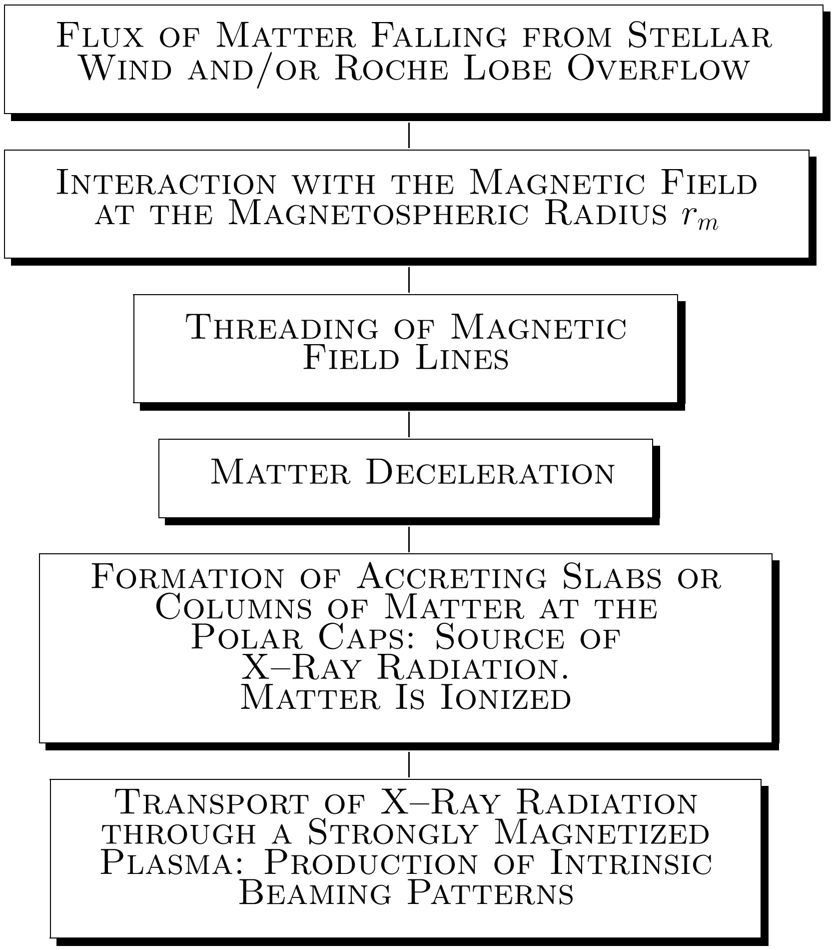

Fig. 1. Schematic block diagram of the physical processes occurring in a X–ray binary pulsar accreting from its companion. For a detailed discussion on the physics involved in each block see Orlandini (2004).

properties it is therefore necessary to describe the interactions of the X–rays produced at the NS surface with the highly magnetized plasma forming the magnetosphere (see, e.g. Mészáros, 1992). This is a formidable task because we cannot use a linearized theory for the radiative transfer equations but we have to deal with the fully magnetohydrodynamical system. In Fig. 1 we present a very schematic block diagram of the physical scenario that describes the production and emission of pulsed X-rays from XBPs (Orlandini, 2004).

From the picture given above it should be clear that in order to be able to

describe the XBP spectra it is first necessary to understand how radiation is formed and then to study how this radiation interacts with the strongly magnetized plasma of the NS. As a consequence of this interaction, cyclotron resonance features (CRFs) are observed in XRB spectra (for a recent review see Harding, 2003). Because of their broad character, CRFs are quite sensible to the continuum modelization. After a review on the mechanisms of spectral formation in XBPs, I will present the case study of the Vela X–1 CRFs and their dependence on the continuum adopted.

2 Spectral formation mechanism in XBPs

Once matter has penetrated the NS magnetosphere, it will follow the magnetic field lines up to the magnetic polar cap, where it will be decelerated (see Fig. 1). If the amount of matter falling onto the polar caps is high enough that an X–ray luminosity greater than about 10^{37} erg/s is reached, then a radiation-dominated (collisionless) shock will form at some distance above the NS surface, creating an accretion column (Basko and Sunyaev, 1976). For luminosities lower than 10^{37} erg/s the radiation pressure is not sufficient to stop the infalling matter, which therefore can impact directly onto the NS. In this case the source of X–ray radiation is an accretion slab and emission occurs in a direction parallel to the magnetic field (pencil beam), while in the case of emission from an accretion column X–rays are emitted from the sides of the column (fan beam) because the column is optically thick to X–ray radiation. It is clear that the formation or not of an accretion column (that is, of a collisionless shock) depends on how much X–ray radiation is produced which, in turn, depends on the radiative transport through the infalling matter. In other words, the flow dynamics and the radiative transport are coupled, in a sort of “feedback effect”.

From a theoretical point of view, the main physical mechanism of emission in XBPs is (inverse) Compton scattering. According to the the value of the Comptonization parameter y, we expect to observe a (modified) blackbody spectrum if $y \ll 1$, while for $y \gg 1$ inverse Compton scattering can be important. If we define a frequency $\omega_{\rm co}$ such that $y(\omega_{\rm co}) = 1$, then for $\omega \gg \omega_{\rm co}$ the inverse Compton scattering is saturated and the emergent spectrum will show a Wien hump, due to low-energy photons up-scattered up to $\hbar\omega \sim 3kT$ (Rybicki and Lightman, 1975). In the case in which there is not saturation a detailed analysis of the Kompaneets equation shows that the spectrum will have the form of a power law modified by a high energy cutoff (Rybicki and Lightman, 1975; Sunyaev and Titarchuk, 1980).

Numerous attempts were made to numerically simulate XBP spectra (see e.g. Mészáros and Nagel, 1985a,b). While there was a qualitatively agreement with

the observations, an *ad hoc* source of soft photons was required in order to fit the low energy part of the spectrum. This low energy thermal emission was discussed into detail by Hickox et al. (2004). They find that, in the case of luminous ($\gtrsim 10^{38}$ erg/s) pulsars, the most likely origin of this soft excess is the reprocessing of hard X–rays (produced by the NS) by optically thick material. This process can be excluded for less luminous sources ($\lesssim 10^{36}$ erg/s), for which the most likely origin of the soft emission is from the NS surface or circumstellar matter heated by the NS emission. For intermediate luminosities XBPs are likely present both kind of emission.

Recently, Becker and Wolff (2005a,b) renewed the interest on spectral formation in XBPs by introducing, in the presence of an accretion column, the effect of bulk or dynamical Comptonization. In the accretion column, the infalling electrons that act as scattering medium for the soft photons possess a preferred motion: this implies that photons gain energy through first-order Fermi acceleration. In the case considered in the past of the thermal Comptonization process, photons gain energy via second-order Fermi acceleration because of the incoherent, stochastic motion of the plasma. Therefore the energization process occurs at the expense of the bulk kinetic energy of the infalling matter and is not supplied by the gas internal energy. In this scenario the soft component comes out naturally from soft photons produced by the "thermal mound" at the base of the accretion column that are able to escape without experiencing many scatterings.

Taking into account *only* bulk Comptonization and neglecting cyclotron emission and absorption, Becker and Wolff (2005b) were able to reproduce qualitatively the general form of a XBP broad-band spectrum: they predict a high energy power law and a turnover at low energy. This model is not able to explain the high energy cutoff observed in many XBPs, but this is probably due to the not inclusion of cyclotron processes: indeed the cutoff energy and the cyclotron resonance feature (CRF) energy are strongly correlated (Makishima and Mihara, 1992).

3 Comparison with observations

From an observational point of view the phenomenological model able to describe the broad-band spectra of accreting XBPs contains (i) a black-body component with temperature of few hundreds eV; (ii) a power law of photon index $\sim$1 up to $\sim$10 keV; and a (iii) a high energy ($\gtrsim$ 10 keV) cutoff that makes the spectrum rapidly drop above $\sim$40–50 keV (see, e.g. Orlandini and Dal Fiume, 2001; Coburn et al., 2002; Filippova et al., 2005). Superimposed there are emission line features due to fluorescence from ions at different ionization levels, and broad absorption "lines" due to cyclotron resonances. In Fig. 2

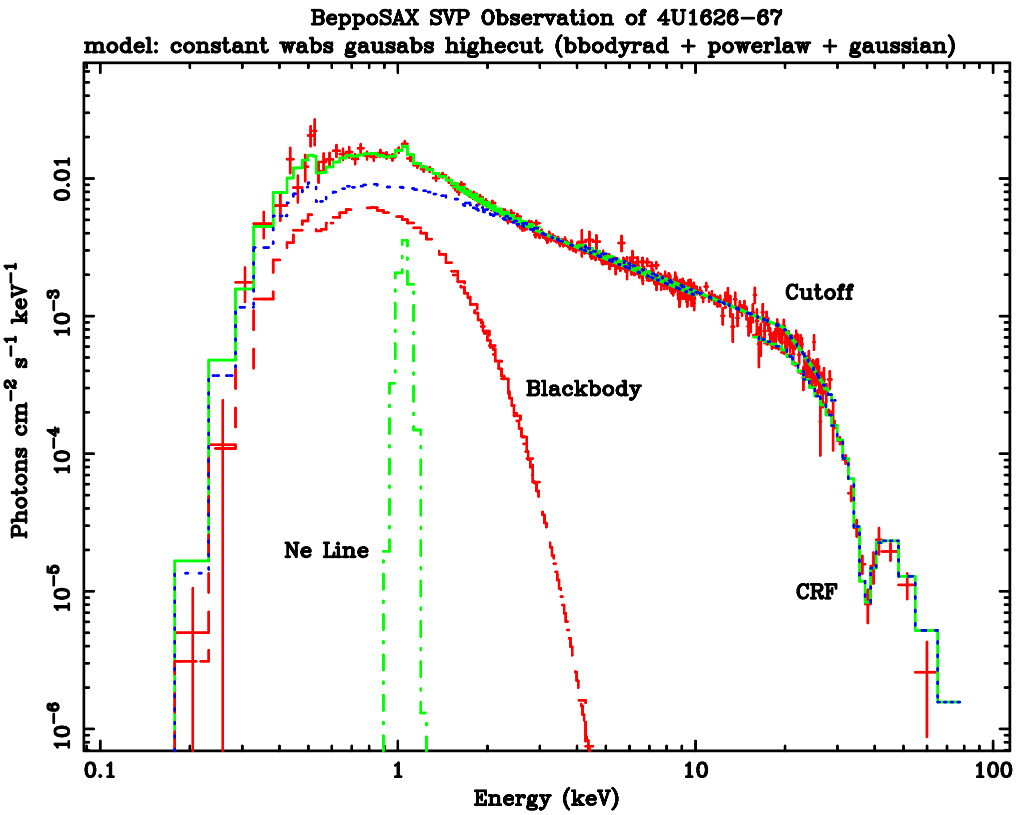

Fig. 2. 0.1–100 keV pulse averaged spectrum of the XBP 4U 1626–67 as observed by BeppoSAX (Orlandini et al., 1998b). All the typical XBP spectral components described in the text are present in this source.

we show the BeppoSAX 0.1–100 keV, pulse averaged spectrum of the XBP 4U 1626–67 (Orlandini et al., 1998b), in which all the components mentioned above are clearly present.

The first description of the high energy spectral rollover was quite crude (White et al., 1983), and Tanaka (1986) "smoothed" the cutoff by introducing the so-called Fermi-Dirac cutoff. By analyzing a sample of XBP spectra observed by *Ginga*, Mihara (1995) introduced the so-called NPEX (Negative Positive Exponential) model:

$$\mathrm{NPEX}(E) = (AE^{-\alpha} + BE^{+\beta}) \exp\left(-\frac{E}{kT}\right)$$

the components of which have a physical meaning because, if $\beta = 2$, it mimics the saturated inverse Compton spectrum (see discussion in Orlandini and Dal Fiume, 2001). Furthermore, because the (non relativistic) energy variation of a photon during Compton scattering is $\Delta E/E = (4kT - E)/mc^2$ (Rybicki and Lightman,

1975) then when $E = E_{\rm cyc}$, with $E_{\rm cyc}$ the CRF energy, the medium is optically thick and therefore $E_{\rm cyc} \sim 4kT$. In other words, the measurement of the CRF energy gives an order of magnitude estimate of the temperature of the electrons responsible of the resonance.

3.1 The CRFs in Vela X–1

The knowledge of the form of the continuum is of paramount importance for the determination of the physical parameters derived from broad features, as CRFs. In Fig. 3 we show the fits with different spectral models to the BeppoSAX 0.1–100 keV, pulse-averaged spectrum of one of the best studied XBPs, Vela X–1. This source presents a controversial CRF at ~ 25 keV and a well determined CRF at ~ 50 keV (Orlandini et al., 1998a; Kreykenbohm et al., 2002). In order to check if the first CRF is real or an artifact due to a incorrect modelization of the continuum, we fit the spectrum with three different continuum models: a broken power law (top panel in Fig. 3), and two cutoff power laws (second and third panel). In the first case we needed *two* CRFs, while in the other two cases only one CRF at ~ 50 keV was required. In the second and third panel we modeled the CRF with the CYCABS model (Mihara, 1995), and a Gaussian in absorption (Soong et al., 1990), respectively. In order to extract the CRF profile from the residual panel, we put to zero the CRF normalization. It is quite evident from the residual panels in Fig. 3 that the CRFs strongly depend on the choice of the continuum model (from an F–test they result statistically equivalent): the ~ 25 keV features is surely present with a broken power law continuum (although its energy is quite close to the break energy) while it disappears if using two cutoff power laws. In this latter case there is a hint of its presence by using a CYCABS modelization of the CRF, while it is not present at all by using a Gaussian in absorption. A pulse phase spectroscopy performed on a longer BeppoSAX observation confirmed this result (La Barbera et al., 2003). We think that this feature could be due to a two-step steepening of the spectrum modeled with an incorrect smooth rollover, as already observed in the XBP OAO 1657–415 (Orlandini et al., 1999).

4 Conclusion

After more that 30 years from their discovery, there is not yet a satisfactory theoretical model for the spectral emission in XBPs able to explain the observed spectra. Even if the recognition of the importance of bulk Comptonization is opening new insight in the comprehension of this quite complicated issue, it is the lack of a theoretical treatment of Compton scattering in the

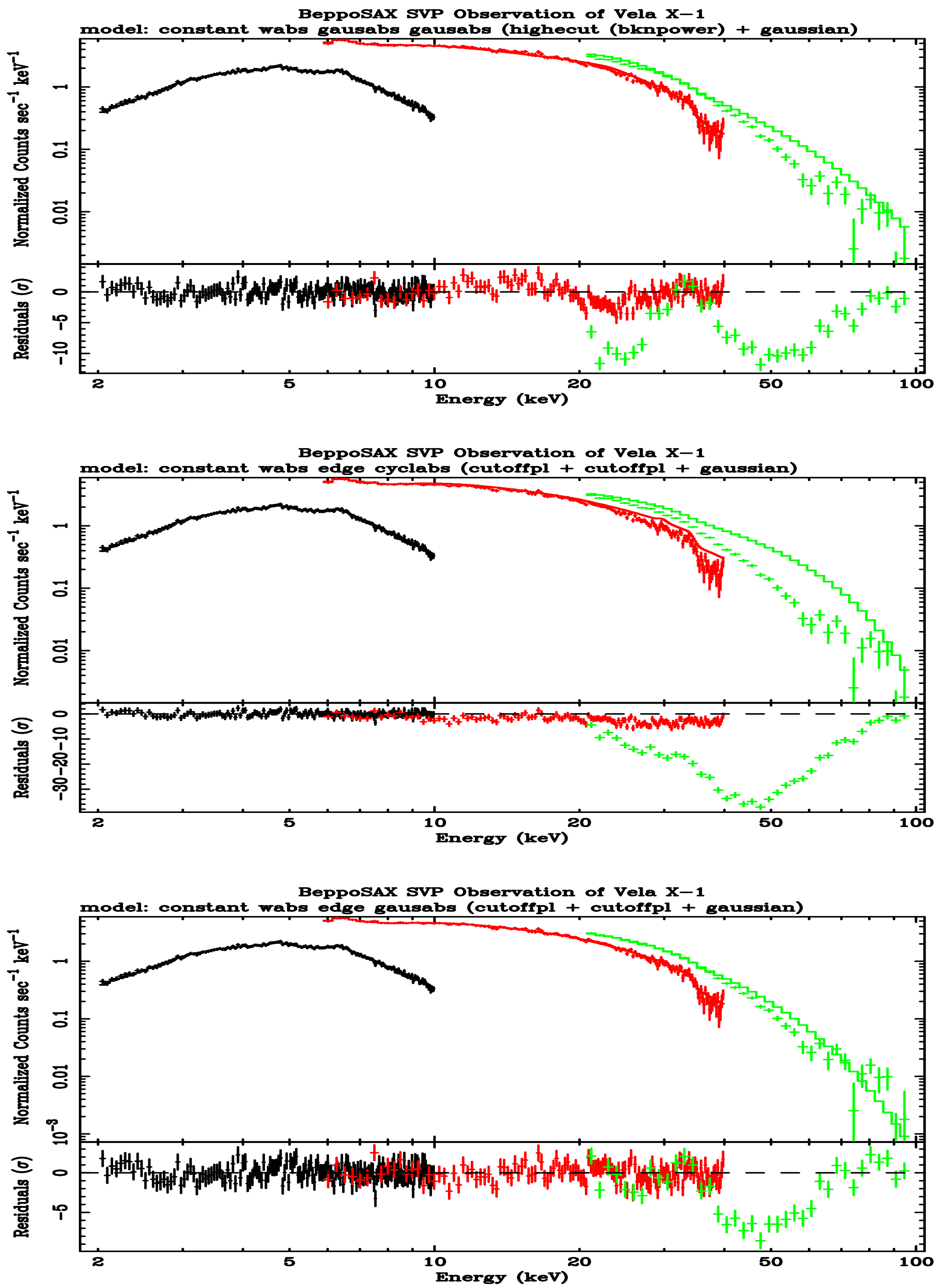

Fig. 3. BeppoSAX Vela X–1 broad-band spectrum fit with three different spectral models (Orlandini et al., 1998a). The residual panels show the CRF profile obtained by putting the line normalization to zero. See text for the model descriptions.

presence of strong magnetic fields the likely culprit of our poor understanding of spectral formation XBPs.

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